

Characterisation and Modelling of the Dynamic Behaviour of a Shape Memory Alloy Element

M. Collet, E. Foltête, C. L'Excellent, P. Malécot*

Laboratoire de Mécanique Appliquée, Université de Franche-Comté, France.

ABSTRACT

Shape Memory Alloys (SMA) are now well recognized as potential materials for structural control. The optimised integration of some SMA devices in a mechanical structure for passive structural damping requires a predictable modelling. At first experimental and numerical studies have been performed on a CuAlBe beam under harmonic flexion, leading to a qualitative modelling based on the material thermomechanical laws.

We present here a full set of experiments where the behaviour of martensitic CuAlBe elements is characterised for tension in a small frequency range, typically from 0.1 to 5Hz. A dynamic modelling is then proposed and compared with the experimental results.

1. INTRODUCTION

Since some years, the materials are not only investigated for their good thermomechanical properties (high yield elastic limit or resistance) but also for their functional properties (sensor, actuator...). Hence some of them as piezoelectric, magnetostrictive, ferroelectric or shape memory alloys can be examined as 'active' elements of a structure now called an adaptative one. As an example, a material used as actuator constitutes a transducer which is able to generate a mechanical work when an energy corresponding to its active specificity (electric, magnetic, thermal...) is furnished.

An example of vibration control or shifting is the recovery stress induced by heating a prestrained SMA in a martensitic state under maintaining this constant strain state. Moreover in some hybrid composite made of SMA prestrained wires embedded in a resin epoxy matrix, a simple heating of all the wires induces a stiffness modification, and if only some chosen wires are heated, a control of the geometrical shape is obtained. But in these two cases, the time response depends completely on the slow calories flow in the wires.

Nowadays an increasing interest is focused on the real dynamic behaviour of SMA. Liu and Van Humbeeck (Liu and Van Humbeeck, 1997) explained that the high damping capability seems to be related to the hysteresis mobility of the twinned interfaces and defects inside the martensitic phase. They show that the austenitic phase has a smaller damping capability than the martensitic one. In the work of Wu and coworkers (Wu et al., 1995), damping was studied in NiTi alloys as a function of frequency, amplitude and temperature rate. A damping peak was observed in the vicinity of phase transformation during the heating and cooling processes. At last, with the help of the Likhachev model (Likhachev, 1996), Pushtshaenko et al. performed the damping simulation of a shape memory alloy rod under tension-compression. In a first paper (Collet et al., 2001), our objective was to understand the effect of the stress induced phase transformation (a mother phase called Austenite is transformed in a product phase called Martensite). A detailed characterization of a Cu Al Be beam under harmonic bending was presented.

In this paper, attention is paid to the stress induced reorientation of martensite platelets, using a similar bending CuAlBe beam. To complete this test, cyclic tension experiment on CuAlBe beam are performed. The purpose consists in studying the effect of frequency on the dissipation capacity. That energy dissipation is directly related to the friction between the martensite platelets themselves during the reorientation. Hence a phenomenological equation connecting the axial stress to the total strain can be set up. At last numerical simulation results are given.

2. DYNAMIC EXPERIMENT

2.1. Description

The experimental setup described in figure 1 is the same as in the previous paper (Collet et al., 2001). The only difference is the SMA composition which leads to a fully martensitic state at free stress and room temperature.

Report Documentation Page			<i>Form Approved OMB No. 0704-0188</i>					
<p>Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p>								
1. REPORT DATE 00 JUN 2003	2. REPORT TYPE N/A	3. DATES COVERED -						
4. TITLE AND SUBTITLE Characterisation and Modelling of the Dynamic Behaviour of a Shape Memory Alloy Element			5a. CONTRACT NUMBER					
			5b. GRANT NUMBER					
			5c. PROGRAM ELEMENT NUMBER					
6. AUTHOR(S)			5d. PROJECT NUMBER					
			5e. TASK NUMBER					
			5f. WORK UNIT NUMBER					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Laboratoire de Mécanique Appliquée, Université de Franche-Comté, France			8. PERFORMING ORGANIZATION REPORT NUMBER					
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)					
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)					
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited								
13. SUPPLEMENTARY NOTES See also ADM001697, ARO-44924.1-EG-CF, International Conference on Intelligent Materials (5th) (Smart Systems & Nanotechnology)., The original document contains color images.								
14. ABSTRACT								
15. SUBJECT TERMS								
16. SECURITY CLASSIFICATION OF: <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 33%; padding: 2px;">a. REPORT unclassified</td> <td style="width: 33%; padding: 2px;">b. ABSTRACT unclassified</td> <td style="width: 33%; padding: 2px;">c. THIS PAGE unclassified</td> </tr> </table>			a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified	17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 7	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified						

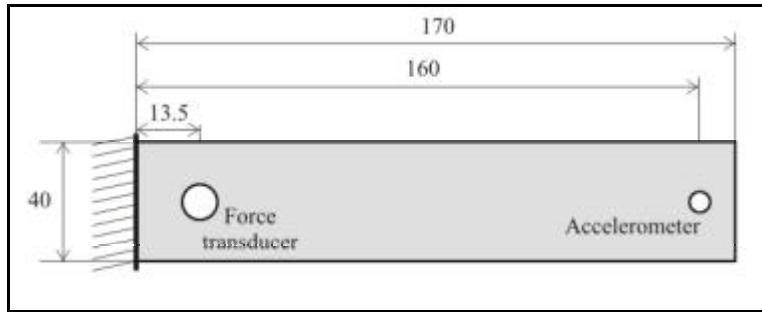


Figure 1. Experimental setup (dimensions are in mm)

The SMA beam is excited by using an electrodynamic shaker. Its response is measured with a lightweight accelerometer located near the free end.

2.2. Random excitation

The first measurements have been performed under random low level excitation. Figure 2 shows the obtained Frequency Response Function (FRF).

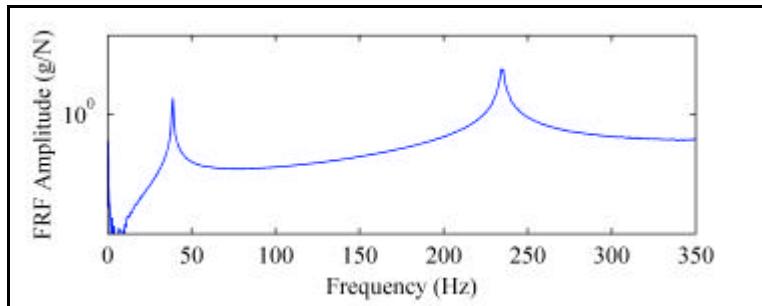


Figure 2. FRF for low level random excitation

The frequencies of the two first bending modes were identified by linear curve-fitting at 38.7 and 234.8 Hz respectively.

2.3. Nonlinear behaviour in time domain

When applying a harmonic input force at the frequency of the first bending mode, the nonlinear behaviour of the beam can be directly observed on the time response (figure 3). Increasing the amplitude of the input force causes a strong distortion of the response, due to harmonic resonances.

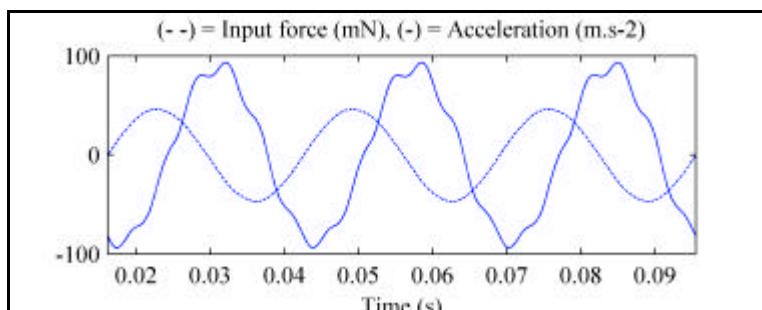


Figure 3. Time response under harmonic excitation

A spectral analysis of the response signal shows a significant participation of the 6th harmonic, which frequency is close to the second bending mode.

2.4. Nonlinear behaviour in frequency domain

Frequency domain analyses based on the Fourier transform are suitable for linear systems only. It must therefore be kept in mind that the following results are based on the first harmonic approximation. Nevertheless they bring us information on the damping capabilities of the SMA.

The following results were all obtained through sine stepping measurements with constant force amplitude. Figure 4 shows the evolution of the FRF amplitude when increasing the input force level. The peak with the higher frequency and amplitude corresponds to the lower force level.

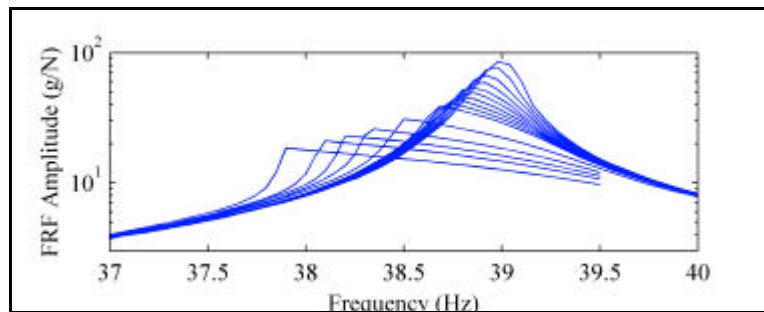


Figure 4. FRF amplitude for 15 force levels from 0.012 to 0.45 N

Increasing the force affects the FRF in a quite classical manner for nonlinear systems: the apparent resonance frequency decreases, the symmetry of the peak is progressively lost and a jump phenomenon occurs.

Figure 5 shows the Nyquist diagrams of the FRF for 5 significant force levels. The damping effect due to martensitic platelets reorientation is clearly visible.

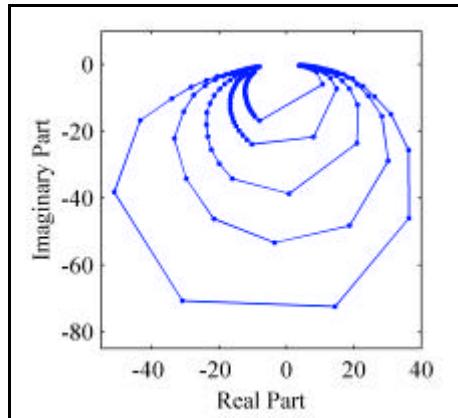


Figure 5. Nyquist diagram for 5 significant force levels

Finally, figure 6 shows the FRF amplitude for three different force levels, measured successively with ascending and descending excitation frequency sweep. The jump frequency for the increasing sweep is always higher than for the descending one. It is also clear that the nonlinear effect increases with the force amplitude.

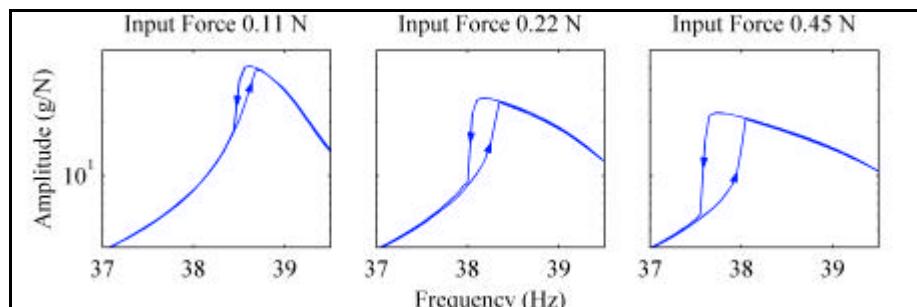


Figure 6. Ascending and descending sine stepping tests

3. CYCLIC EXPERIMENT

3.1. Description

The experimental setup is described in figure 7. The experiments were performed on a fully martensitic state at free stress and at room temperature CuAlBe (reference AH 42 tréfimétaux France). The weight composition of the shape memory alloy used is Cu : 88% Al: 11.5 % Be: 0.5 %. The tensile machine used during the experiments is a INSTRON model 8501.

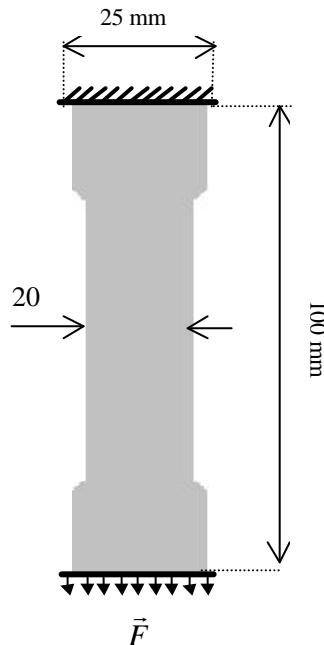


Figure 7. experimental setup

3.2 Process

The main purpose of this experiment consists in studing the behaviour of a martensitic SMA at different frequencies. Due to the machine limitation we try three “low” frequencies : 0.1Hz , 1 Hz , and 5Hz .A more developed tests on the same alloy with another tensile machine are forcasted to attain higher frequencies and to test the compression behaviour. Each cantilever sample has been cycled for 50 cycles between 2 % and 1,40% (as described in figure 8) to remain in a tension state.

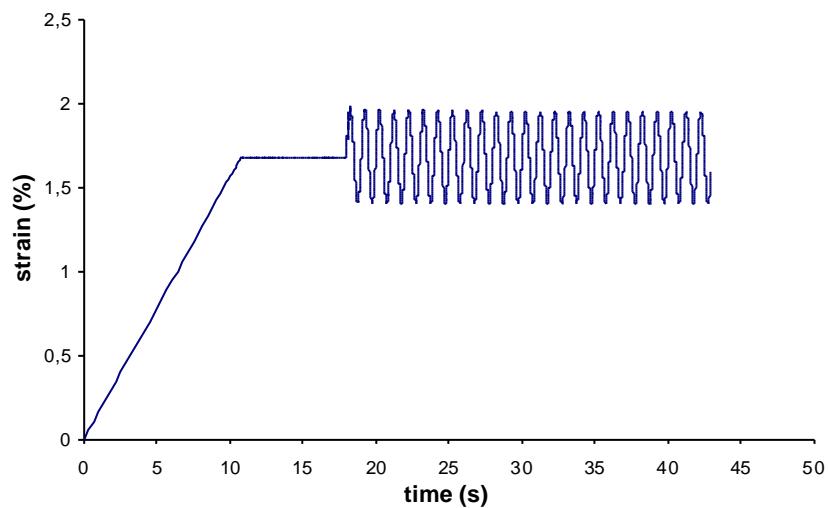


figure 8. example of fixed stress for cycling at 1Hz

The major difficulty was for the 5 Hz frequency test. Indeed the stress control was less precise at this frequency that's why the results were more complicated to obtain.

3.3 Results

The results we get for each frequency are not given here, but we can see an example of the cyclic results for the 1 Hz frequency on the figure 9.a. Comparing the cycles given by the 0.1 and 1 Hz frequency tests (figure 9.b) it's possible to observe a slope difference due to the strain rate velocity and a diminution of the loop area due to the number of cycles.

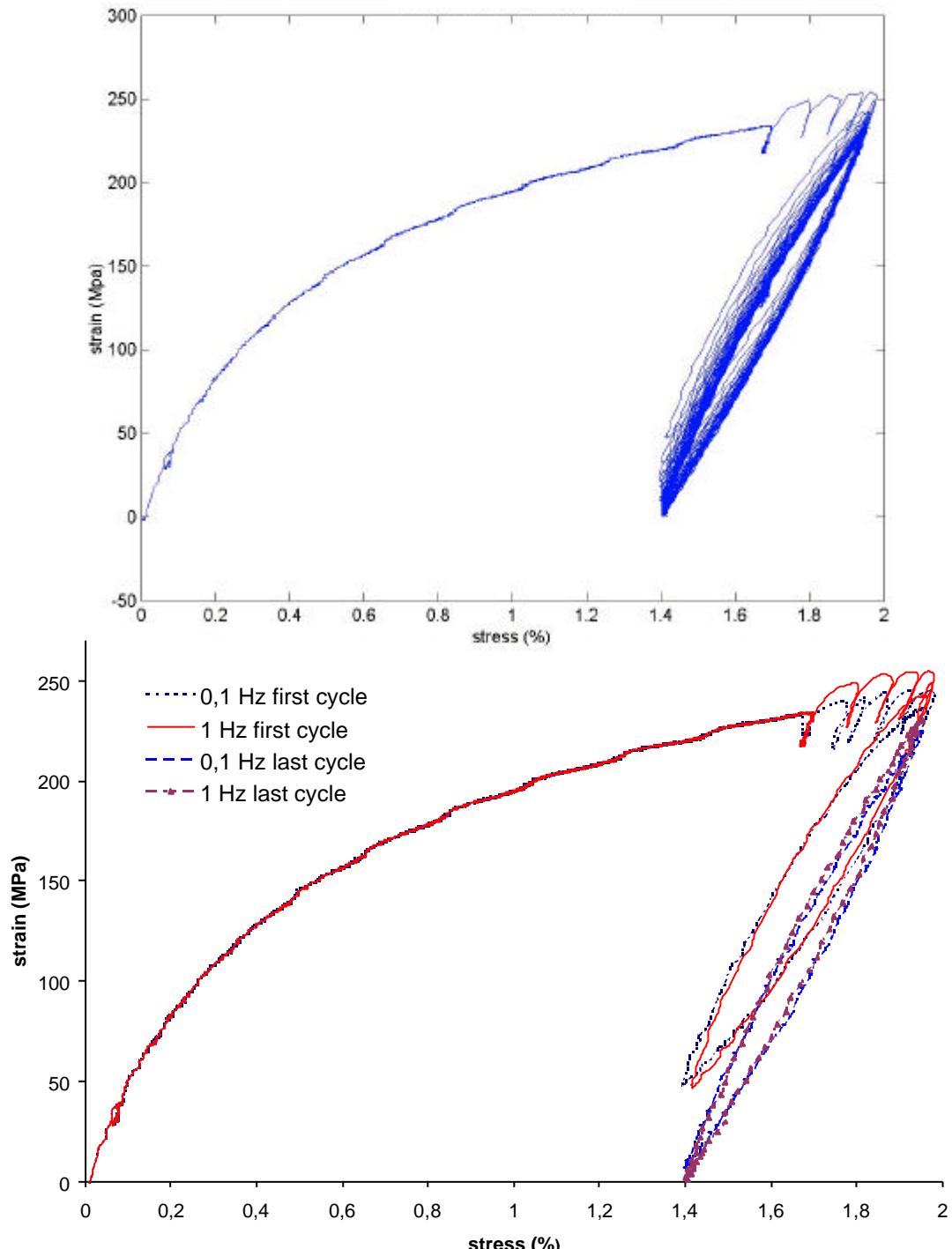


figure 9.a : 50 cycles at 1 Hz

figure 9.b : first cycle and last cycle at 0.1 and 1 Hz

This experimental results will permit to have a better understanding of the martensite reorientation to modify the model described in the next part. The integration of the martensite reorientation process has begun but it's not enough developed to be presented here.

4. THERMOMECHANICAL MODEL

4.1. Detailed Model

The detailed thermomechanical model used to describe the transition from thermal martensite to stress induced martensite can be found in (Boubakar and Lcellent, 2002). It is based on three main equations: the kinetic equation, the driving force associated to the reorientation as a function of the strain and the internal interactions, and the heat equation.

4.2. Simplified Model

In order to be able to perform the Finite Element simulation of a dynamical test, the detailed thermomechanical model needs to be simplified, as it was done for the austenitic SMA. For this last case, the characteristic diagrams were approximated with affine functions, leading to a great reduction of the number of parameters. This simplified model was then used to define a complex Young modulus which represents the equivalent stiffness and damping associated to one vibration cycle of the beam as presented in the equation 1 (Collet et al., 2001):

$$s = E * (1 + i\hbar) \text{ (eq. 1)}$$

A 1D Finite Element model was finally built. It gave a nice reproduction of the observed behaviour of the beam.

In this model the strain is a function of the stress, the frequency (or the pulsation) and the number of cycles. The cyclic tests presented in part 3 of this paper (fig. 9.a) show that with the increasing number of cycles the SMA tense to an asymptotic behaviour. So we need to express the characteristics of this stabilised cycle which is a function of the maximum applied stress and the frequency to solve the damping evolution problem described in the following part.

4.3. Finite Element Simulations

A 1D Finite Element model has been built by using the previous polynomial exponential approximation. For each vibration cycle and each element of the beam, an equivalent complex Young modulus is computed by solving a nonlinear problem with a minimisation procedure. Figure 10 shows the evolution of the FRF while increasing the force amplitude. The apparent resonance frequency shift and the jump phenomenon show that the stiffness effect is well represented. But the peak amplitude remains constant, indicating that the damping evolution is not correct (see fig.4).

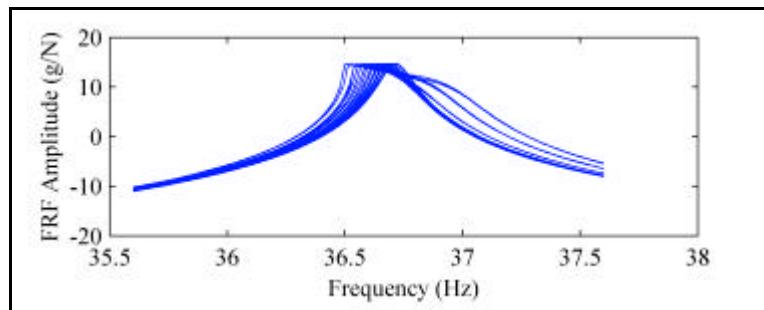


Figure 10. FRF amplitude obtained by Finite Element simulation for different force levels

Finally, the Finite Element simulation of an ascending and descending frequency test is shown figure 11. The jump frequency shift is in good agreement with the experimental behaviour (see fig.6).

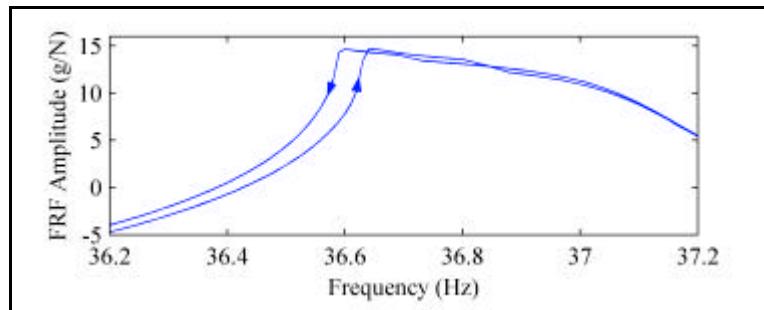


Figure 11. FRF amplitude obtained by Finite Element simulation for ascending and descending frequency

5. CONCLUSIONS

Dynamic and cyclic measurements on a Cu Al Be martensitic beam have been performed. Dynamic measurements show that the reorientation process induces a strongly nonlinear behaviour including nonlinear time responses, resonance frequency shift and jump phenomenon. The great attenuation of the resonance amplitudes confirms that this material has good capabilities for structural control. Nevertheless, the design and optimisation of a SMA device will only be possible if a reliable dynamical modelling is available, but a reliable physical model of cyclic behaviour is available (L'Excellent and Bourbon 96) and is going to be used in this way. Nowadays we use polynomial exponential laws to simplify the thermomechanical model. A Finite Element model based on these considerations has been built. It reveals a good representation of the stiffness evolution versus the force amplitude, whereas the damping effect is not well reproduced. The cyclic tests have been performed in order to improve the modelling of the SMA and more particularly of the damping, but these experimental results have not been used yet. So the numerical simulation needs to be completed.

REFERENCES

Auricchio F., Faravelli L., Magonette G. and Torra V. (2001) *Shape Memory Alloys. Advances in Modelling and Applications*, 1st edn, International Center for Numerical Methods in Engineering, Barcelona, Spain.

Boubakar M. L. and L'Excellent C. (2002), *Some Tools for Modelling Shape Memory Alloys. Thermomechanical Behaviour and Some Efficient Use*. Proceedings of the 3rd World Conference on Structural Control, Como, Italy.

Collet M., Foltête E. and L'Excellent C. (2001) Analysis of the Behavior of a Shape Memory Alloy Beam under Dynamical Loading. *Eur. J. Mech. A/Solids*, 20: 615-630

L'Excellent C., Bourbon G. (1996), *Thermodynamical Model of cyclic behavior of Ti-Ni and Cu-Zn-Al shape memory alloy under isothermal undulated tests.*, *Mech. of Mat.* 24(1996)59-73.

Likhachev V. A. (1996), *Theory of martensitic anelasticity of crystals*, *J. de Phys. IV* C1, 321-333.

Liu Y, Van Humbeeck J. (1997), *On the damping behavior of NiTi shape memory alloy*, *J. de Phys. IV* C5, 519-524.

Pushtshaenko O., Oberaigner E. R., Antretter T., Fisher F. D. and Tanaka K. (2002), *Simulation of the damping of a shape memory alloy rod by using the Likhachev model*, *Int. Mat. Syst. And Struct.*

Wu K., Dalyr S. K., Liu Y. and Pu Z. (1995), *Damping characteristics of R phase NiTi shape memory alloys*, *Proceedings SPIE, Smart Struct. And Mat.* 2441: 139-148.